DIELECTRIC MIXING MODELS FOR CEMENT BASED MATERIALS

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INTRODUCTION

The construction industry has a keen interest in using a nondestructive, real-time, reliable and inexpensive technique for the in-place evaluation of the compressive strength of concrete structures. Compressive strength of concrete is usually determined by drilling a core and testing it in a laboratory. This method is relatively expensive, and it may take a few days for the results to be known. In addition, this method is destructive. Consequently, several nondestructive techniques have been developed for this purpose. These include: pulse velocity method, surface hardness, penetration, pullout, breakoff and maturity techniques [1]. The major disadvantage of these techniques is their limited accuracy, and the fact that they are not totally nondestructive.

Microwave nondestructive testing methods are well suited for inspecting dielectric materials such as cement paste and concrete [2]. When applied to chemically reactive materials such as those in which curing occurs, microwave methods have shown the potential for cure state monitoring as well [3,4]. Porosity level estimation and constituent characterization in homogeneous materials is also possible with these methods [5,3].

Recently, a microwave nondestructive inspection method was used to measure the reflection and dielectric properties of cement paste specimens with various water/cement (w/c) ratios at several frequencies [6]. This method utilized an open-ended rectangular waveguide in-contact with the specimens. Subsequently, the microwave reflection properties of these specimens, at 5 and 9 GHz, were correlated to their w/c ratios and their compressive strengths [6]. The results of these preliminary investigations show great promise for using a true nondestructive testing method for the in-place compressive strength evaluation of concrete based structural members.

To achieve the above goal, more information is needed to evaluate the dielectric properties of cement based mixtures from the dielectric properties and volume content of their respective constituents. Since the reflection properties of a specimen is highly dependent on its dielectric properties, a means for predicting the dielectric properties of cement based materials would result in the estimation of the microwave reflection coefficient. This is the parameter which is subsequently used to estimate the compressive strength or the w/c of the specimen.

In this paper, a two- and a three-phase dielectric mixing model is used to predict the microwave dielectric properties of cement paste mixtures with sand as fine aggregate. Through this study, we hope to extend the scope of applications in which microwave testing methods could be used as a nondestructive tool for the measurement of the compressive strength of cement based structures.

BACKGROUND

Concrete compressive strength, f'_c, is strongly dependent on w/c ratio. Microwave signals are also significantly affected by the presence of water (free or bound). Thus, it is possible that microwave reflection properties of concrete may be correlated to its compressive strength. Consequently, in previous experiments, it was shown that the magnitude of the reflection coefficient ($|\Gamma|$) measured at the aperture of an open-ended waveguide probe, in-contact with cement paste specimens, is also significantly influenced by w/c ratio [6]. Figure 1 shows the schematic of such a measurement approach .

The results of these experiments, were duplicated at 3 GHz in the present study, and showed an increase in $|\Gamma|$ as a function of decreasing w/c ratio (Figure 2). The same relationship was observed for the dielectric property (ε_r) as it is intimately linked to $|\Gamma|$. In [6], a simple expression was developed in which the percent change in $|\Gamma|$ for any specimen compared to that with 0.55 w/c ratio was correlated to a similar percent change in the w/c ratios and the compressive strengths of the specimens. Figure 3 shows this relationship for two different frequencies . The results indicate that using a standard calibration specimen (e.g. cement paste with w/c ratio of 0.55), its reflection coefficient may be measured and compared to that of an unknown specimen. The measured percent change is then used to determine the compressive strength of the unknown specimen from the relationship shown in Figure 3. For a more detailed explanation of the measurements and the results the reader is referred to reference [6].

The goal of the present investigation is to study and predict the dielectric properties of cured cement specimens at J- and X-band in which a fine aggregate (sand) was included in the mixture. Two simple two-phase mixing models are be used to calculate the dielectric properties of the mixture. Since a sand granule is relatively small compared to the wavelength of the exciting wave, the use of a mixing models is warranted [7].

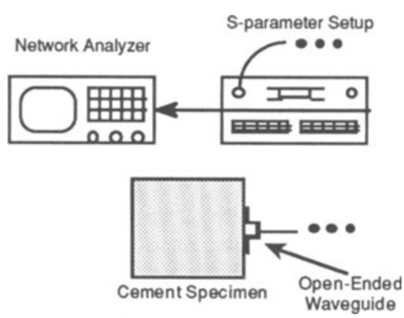

Figure 1. Measurement apparatus.

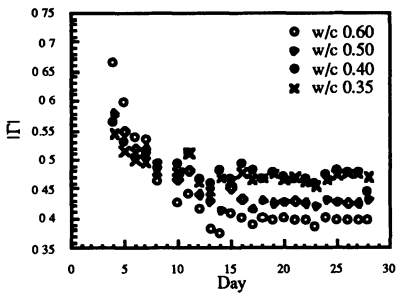

Figure 2. Daily variation of |Γ|.

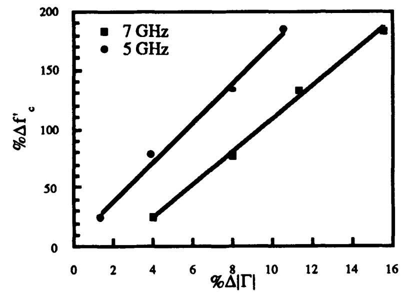

Figure 3. $\Delta f'_c$ vs. $\Delta|\Gamma|$.

If we are able to predict the effective dielectric constant of a mixture from the volume fraction and the dielectric properties of its individual constituents, the reflection properties of the specimen can be readily calculated [8]. Therefore, a scheme similar to that used in [6] could be used to estimate the specimen's compressive strength. The conclusion of this study, once optimized and made robust, would be the implementation of coarse aggregate in our model. The only precaution would then be to ensure that the wavelength of the exciting wave is large enough so that the dimensions of the aggregate are small compared to it.

APPROACH

Four cubic cement paste specimens of 8"x 8" x 8" were prepared with respective w/c ratios of 0.60, 0.55, 0.50 and 0.45. The w/c ratio was calculated by weight. Four additional cubic specimens were prepared with the same respective w/c ratios and dimensions but containing two and a half (2.5) times the volume of sand per each unit volume of cement. The specimens were moist cured for 3 days in a hydration room, and then left at room temperature and humidity for 25 days. Their reflection properties were monitored daily through the 28^{th} day when the specimens are considered to have reached their final strength. Each measurement reported here is the average of eight measurements performed on the sides of each specimen. Figures 4 a-d show the variation of $|\Gamma|$ as a function of frequency for the cement paste and cement-sand mixture for all w/c ratio at X-band. As it can be inferred from the sample preparation description, the volume of the sand constituent increases as the w/c ratio decreases. Since it was experimentally determined that sand has a lower dielectric constant than that of cement paste, thus the reflection coefficient of the cement-sand sample is expected to decrease as the w/c decreases as observed in Figures 4 a-d. In the case of the 0.50 and 0.45 w/c ratios, the porosity of the cement-sand specimens is significantly more than that of their paste counterparts. Therefore, the effect of the air as an inclusion should be explicitly considered for these cases and included in the subsequent dielectric mixing models, as it will be seen later.

The relationship between the measured reflection coefficient at the aperture of an open-ended rectangular waveguide radiating into a medium of a given dielectric property is know through [8]. Therefore, the above reflection property characteristics obtained at the last day of measurement can be related to the effective dielectric properties of the mixtures through a two-phase or three-phase mixing model for the 0.50 and 0.45 w/c ratios. The proposed Rayleigh mixing model is of the form [7],

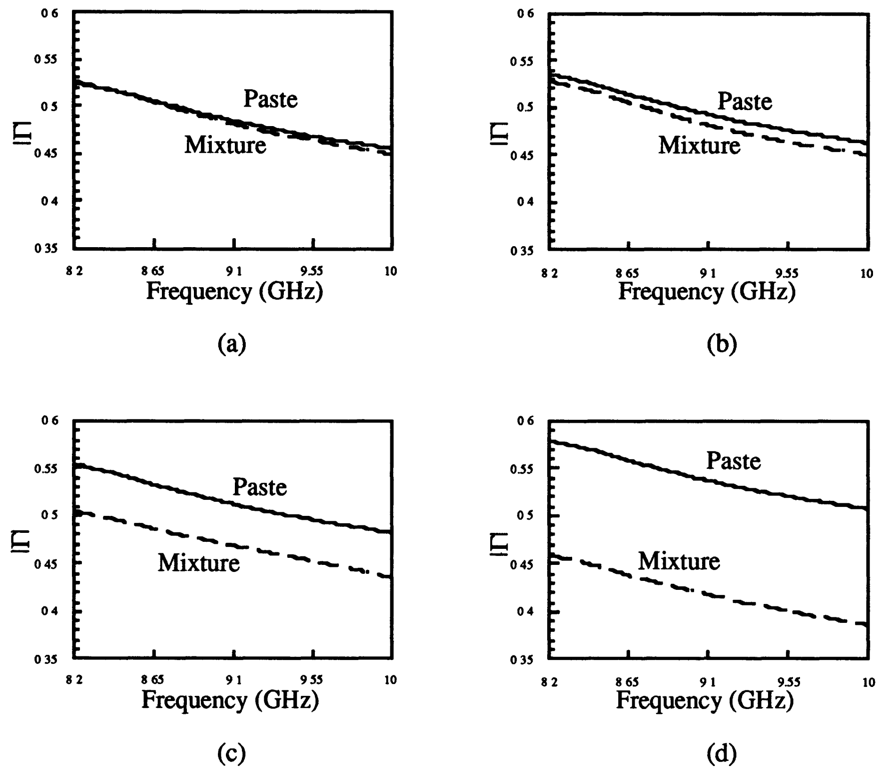

Figure 4. Measured |Γ| vs. frequency for cement paste (solid line) and cement-sand mixture (dashed line) for a) 0.60 w/c, b) 0.55 w/c, c) 0.50 w/c and d) 0.45 w/c.

$$\frac{\varepsilon_{eff} - \varepsilon_{host}}{\varepsilon_{eff} + 2\varepsilon_{host}} = \frac{\varepsilon_{inc} - \varepsilon_{host}}{\varepsilon_{inc} + 2\varepsilon_{host}} \tag{1}$$

and Pearce mixing model given by [7],

$$\frac{\varepsilon_{eff} - \varepsilon_{host}}{\varepsilon_{eff} - \varepsilon_{host}} = \frac{(1-k)f_{inc}}{1-kf_{inc}} \tag{2}$$

in which k is an empirical factor which, in our application, is considered constant per waveguide band.

EXPERIMENTAL MODELING

The individual constituents used in the models are cement paste, sand and air (for the case of the 0.50 w/c specimen due to its air content). The values for the permittivity (real part of ε_r) of the cement, for all w/c ratios, were obtained using open-ended rectangular waveguide measurements [8]. The resulting dielectric properties are a combination of cement (Portland type 2), free and bound water, and air in the specimens, which are all water-to-cement ratio dependent. The dielectric properties of sand were measured using a two-port waveguide measurement as described in [9]. The case of the 0.45 w/c was discarded because of the non-repeatability of the measurements. Such a sample is so porous that its compressive strength would be very low anyway.

i) Two-phase model

The model used for the 0.60 and 0.55 w/c ratio specimens is given by Pearce. To determine the empirical factor *k*, we use (2) and solve for *k* considering the host material (ε_{host}) is chosen to be the cement paste, and the inclusion to be sand (ε_{inc} = 3.1 - j0.05). The waveguide band constant *k* factor is calculated from the 0.55 w/c sample since they presented less measurement variations. For X-band, *k* = 0.597 - j 0.049 and at J-band, *k* = 0.206 - j 0.299.

Figures 5-8 present a comparison between the modeled two-phase mixture with the measured permittivity for the 0.60 and 0.55 w/c ratio. Since mixing models are based on the premise that the size of the inclusion is much smaller than the wavelength of the exciting wave, then we would expect better results at J-band. As it can be appreciated from figures 5 and 6, there is very good agreement between the empirical and the experimental results at J-band. Although some discrepancies exist between the empirical and experimental results at X-band, as presented in Figures 7 and 8, the model seems to predict the mixture well. These discrepancies are partially due to the fact that the inclusions appear larger at higher frequencies, therefore the mixing model does not fully predict the dielectric behavior of the mixture. From these results, it can therefore be inferred that as the operating frequency is lowered, the *k* factor is more universal from sample to sample.

ii) Three-phase model

Since the 0.50 w/c ratio specimen contains non-negligible air content with respect to cement paste, it is deemed necessary to introduce air as a third constituent. To implement the three-phase mixing model, the Rayleigh mixing model is utilized. In this particular case, the host material is the empirical result obtained through Pearce's model, in which only cement paste and sand are considered, and the inclusion (ε_{inc}) is chosen to be air (ε_r = 1.0-j0.0). The volume fraction of air was estimated to be 8% of the total volume. If this estimate is accurate, agreeable results should be observed for the modeling at both bands for this case.

As it can be appreciated from Figures 9 and 10, the fitting of the mixture by the two-phase model is less than acceptable; but once the contribution of air is taken into account via the three-phase mixing model, the model and the experimental data agree quite well. The assumption on the air content of the sample was supported since it produces good agreement at both bands. The ramification of the implementation of the three-phase model would result in determining the porosity of a specimen knowing *a priori* the w/c ratio and the amount of aggregate in the mixture. This could be done via a multi-band measurement.

As described in [8], it is shown that the magnitude of the reflection coefficient, which is the parameter previously correlated to the compressive strength of cement paste, is primarily a function of the permittivity. Although results for the imaginary part of the modeled dielectric constant are not presented here, the modeled and experimental data show reasonable agreement or follow the trend of each other. Discrepancies between the theoretical and experimental imaginary part of the dielectric constant are more of a theoretical concern than a practical one. In future work, more emphasis will directed to improving the fitting of both the real and imaginary part of the dielectric constant. A more thorough formulation describing the behavior of the open-ended waveguide probe as a function of the permittivity of the specimen and other mixing models will studied to this end.

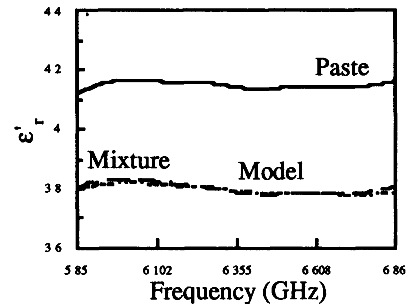

Figure 5. J-band results for 0.60 w/c.

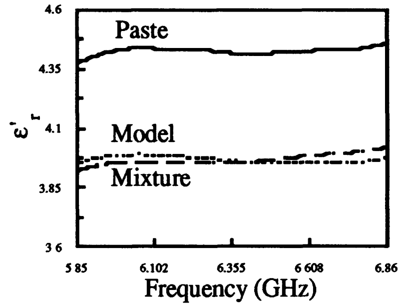

Figure 6. J-band results for 0.55 w/c.

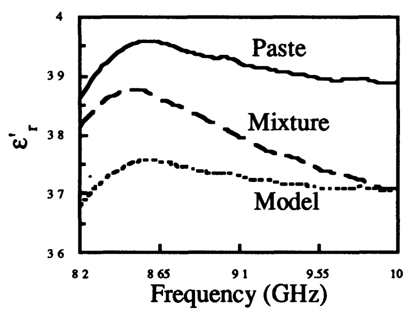

Figure 7. X-band results for 0.60 w/c.

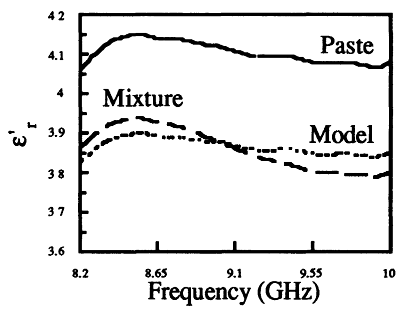

Figure 8. X-band results for 0.55w/c.

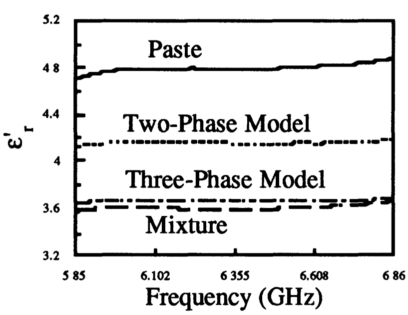

Figure 9 . J-band results for 0.50 w/c.

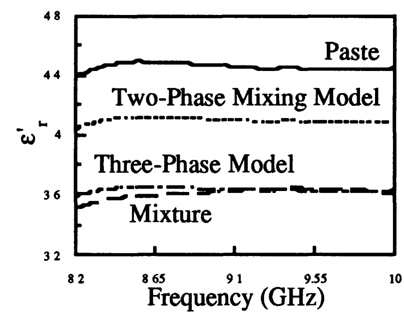

Figure 10. X-band results for 0.50 w/c.

CONCLUSION

An effective dielectric mixing model for cement based materials was used to predict the microwave properties of cured cement based materials. Through this model, it is not only possible to predict the dielectric constant of a multi-constituent cement based material, but also calculate its microwave reflection properties and estimate the porosity of a given specimen. The model, as prescribed by the mixing model premises, predicted the measurement better at the lower frequency bands than at the higher bands. Future work will include the correlation of the microwaves properties to the mechanical properties of cement based mixtures. Also a dynamic time-varying mixing model will be devised to predict the day-to-day microwave properties of the material, contributing to the estimation of the cure-state of cement based structures.

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